Properties of Spiral and Elliptical Galaxy Progenitors at $z > 1$

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Abstract. We present the results of a Hubble Space Telescope and ground-based optical and near-infrared study to identify progenitors of spirals and ellipticals at $z > 1$. We identify these systems through photometric and spectroscopic redshifts, deep K-band imaging, stellar mass measurements, and high resolution imaging. The major modes of galaxy formation, including major mergers, minor mergers, and accretion of intergalactic gas, and their relative contributions towards building up the stellar masses of galaxies, can now be directly measured using these data.

1 Introduction

The generally accepted modern hierarchical galaxy formation picture consists of galaxies forming in dark matter halos that later merge to form larger halos and more massive galaxies. The end result of this evolution is the morphological and stellar population mix in the nearby universe. This picture, however, remains largely untested. Understanding how the modern galaxy population was put into place requires understanding when and how stars (and hence galaxies) formed. Based on several decades of observations and modeling of stellar evolution we know that the stars in nearby galaxies contain a wide diversity of ages and metallicities. To first order these differences correlate with galaxy type and environment. Generally, early-types or elliptical galaxies are dominated by old stars and are found in dense environments, while later type galaxies have a mix of young and old stellar populations and are found in lower density areas.

Directly measuring the galaxy mass assembly and star formation history has now been accomplished out to $z \sim 3-6$. However, these measurements do not tell us *how* galaxies formed. One way to address this question is to include high resolution imaging, such as from deep Hubble Space Telescopes (HST) images. Imaging surveys with HST show that galaxies evolve into normal systems from peculiars between $z \sim 1-2$ (~ 10 Gyrs ago) (Figure 1; e.g., van den Bergh et al. 2001; Conselice et al. 2003). At redshifts higher than $z \sim 1.5$ most galaxies are distorted and asymmetric (Abraham et al. 1996; Conselice et al. 2003). Deep NICMOS observations of the Hubble Deep Field North, which samples the rest frame B-band morphologies of galaxies at $z > 1.2$, demonstrates that these galaxies are intrinsically distorted in the rest-frame optical, and that we are not witnessing morphological k-correction effects (Papovich et al. 2003).

These high redshift galaxies are also undergoing large amounts of star formation (e.g., Madau et al. 1998), creating the normal bright galaxies we see today.

What causes the structural peculiarities in these galaxies, and presumably also the induced star formation? If we can answer this it will reveal the formation modes of galaxies, and allow us to quantify the relative contributions of different formation processes.

2 Mass Assembly as a Function of Morphology

The first step towards understanding the formation mechanisms of galaxies is to have a robust determination of how the structures of galaxies change with redshift, and how these changes relate to the star formation and mass assembly history. Figure 1 shows co-moving number, luminosity, and stellar mass densities of ellipticals, spirals, and peculiar galaxies as a function of redshift. One interesting trend from this figure, besides the dominance of spirals and ellipticals at $z < 1.5$ and peculiars at $z > 1.5$, is the fact that there exists an equilibrium point at $z \sim 1.5$ where the relative fraction of luminosity, mass and number densities for normal galaxies (disks/ellipticals) and peculiars are nearly equal. In all regards this is the redshift in galaxy evolution where modes of forming galaxies are rapidly transitioning. This trend is also seen when studying the NICMOS observations of the Hubble Deep Field North and in the Hubble Deep Field South.

There is a growth in both the stellar mass density and number density of spirals and ellipticals at $z < 1$, with a corresponding decrease in the number of peculiars (see also Brinchmann & Ellis 2000). Star formation is still occurring in disks and ellipticals at $z < 1$ as the stellar mass densities for these types grows by a factor of two or more (Figure 1). The luminosity density for both ellipticals and spirals also peaks at $z \sim 1$, and mass to light ratios for these systems increase with lower redshift at $z < 1$. At $z > 2$ peculiar galaxies consistent with major merging (Conselice et al. 2003) are dominating the luminosity and stellar

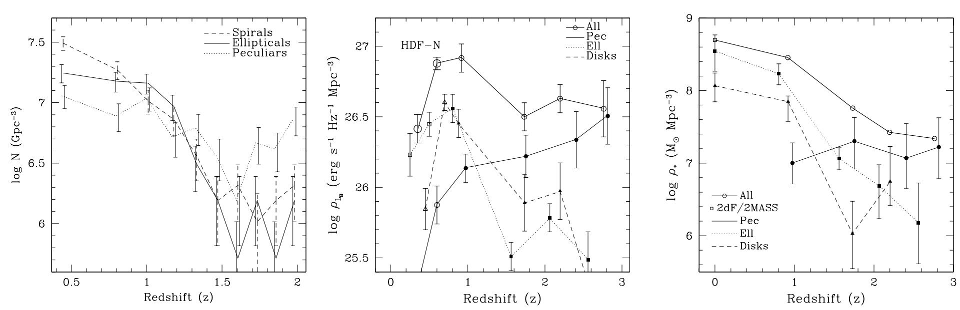

Fig. 1. The relative co-moving number, rest-frame B-band luminosity, and stellar mass density of galaxies as a function of redshift from deep NICMOS images of the Hubble Deep Field North (Conselice et al. 2004a). Points at redshifts $z < 0.5$ are taken from Brinchmann & Ellis (2000), Fukugita et al. (1998) and the 2dF/2MASS survey.

mass density, suggesting that this is the dominate star formation process at early times.

3 Tracing Galaxy Formation

There are four major global methods by which galaxies can form, or how star formation is triggered. One is through major mergers where galaxies are built up by merging with systems of similar mass. The other is through minor mergers where the mass of a galaxy is built up by the accretion of less massive galaxies. The third method is through accretion of intergalactic gas which forms stars around galaxies in disk like structures (Abadi et al. 2003). A fourth is through tidal interactions with nearby galaxies. This is perhaps an over simplification of the star formation triggering process, but it is a valuable starting point for understanding galaxy formation.

The quantitative structural properties of galaxies reveal the formation mechanisms responsible for producing galaxy and star formation (e.g., Conselice 2003). We can use the structures of galaxies, including their sizes and stellar masses, to argue which systems at high redshifts are likely progenitors of either disks or spheroidal components. Figure 2 shows the brightest galaxies at $1 < z < 2$ selected in the near infrared in the GOODS south field (Giavalisco et al. 2004). These systems must be the progenitors of disks and ellipticals and many show structures suggestive of this.

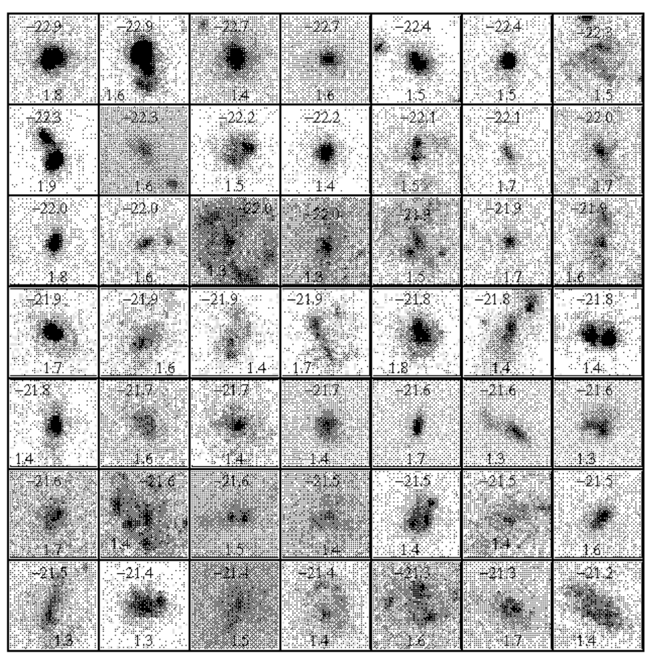

Fig. 2. Examples of galaxies in ACS GOODS images whose photometric redshifts place them at $1 < z < 2$. These are ordered from brightest to faintest down to $M_B = -21$. The upper number is the M_B of each galaxy and the lower number is its redshift. There is a large diversity of properties, from systems that appear very peculiar to those that look similar to normal galaxies. Scale of these images is $\sim 2''$ on each side, which corresponds to about 17 kpc at these redshifts.

3.1 Major Mergers - Spheroid Formation

Major mergers occur when two galaxies of similar mass merge together to form a more massive system. Galaxies which are undergoing major mergers can be identified in the rest-frame optical through their large asymmetries in comparison to other parameters, such as color or clumpiness (Conselice et al. 2000; Conselice 2003). We can use the asymmetry index to determine how common major mergers are at various redshifts and to measure properties of these mergers. The results of this are shown in Figure 3 which plots the inferred merger fraction as a function of redshift for galaxies at two luminosity limits. It appears that most major mergers at high redshift occur in luminous systems. This is also the case for the most massive galaxies at the same redshifts (Conselice et al. 2003). About 50% of the most luminous and massive galaxies at high redshift are undergoing major mergers. The merger rate for the most luminous and massive systems however rapidly declines at lower redshifts. A smaller fraction of fainter and less luminous systems are undergoing mergers, suggesting that some other process is responsible for their formation.

Do these mergers add enough material to produce a massive galaxy at low redshift from the most massive and brightest systems found at $z > 2$? This is uncertain, as it depends not only on the merger rate, but also on the induced star formation produced through the merger. Integrating the mass obtained through major mergers (Figure 3) with reasonable and empirical assumptions about star formation histories induced by mergers, it appears that massive ellipticals can be formed through multiple merger and starbursts. However, a large fraction of stars cannot have formed through major mergers, given that the fraction of galaxies involved in major mergers declines rapidly at $z < 2$ and stellar mass is still assembled at these redshifts (e.g., Dickinson et al. 2003). Figure 3 also shows that the measured merger fraction is lower at low-z than what is predicted in

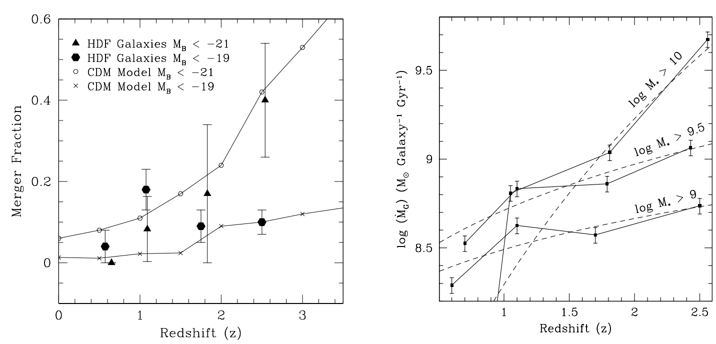

Fig. 3. Left panel: major merger fractions to $z \sim 3$ at magnitude limits $\mathrm{M_B} = -21$ and -19. Semi-analytical model predictions are also shown. Right panel: Stellar mass accretion history from major mergers as a function of initial mass (see Conselice et al. 2003).

CDM models, such that there are too many major mergers produced in these models at low redshift. That is, massive galaxy formation occurs earlier than predicted in semi-analytic CDM models.

3.2 Minor Mergers

Minor mergers are likely a major method for building up the masses of galaxies, as predicted in simulations (Murali et al. 2002). The observed role of minor mergers is however not know with certainty, simply because it is difficult to identify them, as they do not produce major structural effects on galaxies. One clue that minor mergers might be occurring in large numbers at $z < 1$ is that about 50% of the total stellar mass in the universe appears to form at $z < 1$; yet major mergers are not producing this increase (Conselice et al. 2003). The properties of minor mergers can be studied out to $z \sim 1$ most effectively using pair studies of galaxies either in the optical (Patton et al. 2002) or in the near infrared (Bundy et al. 2004). The optical pair fraction suggests that minor merger rates are high enough to produce suitable increases in stellar mass. The merger rate is, however, lower when studying pairs in the near infrared (Bundy et al. 2004). The reason for this is that pre-accreted satellite galaxies are star forming with low mass to light ratios, resulting in a lower near infrared pair fraction. The amount of stellar mass added to galaxies through minor mergers at $z < 1$ is roughly equal to the gain in stellar mass at these redshifts, although this is likely a coincidence (Bundy et al. 2004). However, if these merging/interacting satellites are creating new stars with a total stellar mass equal to that of the original satellite, minor mergers would produce enough mass through tidally induced star formation to

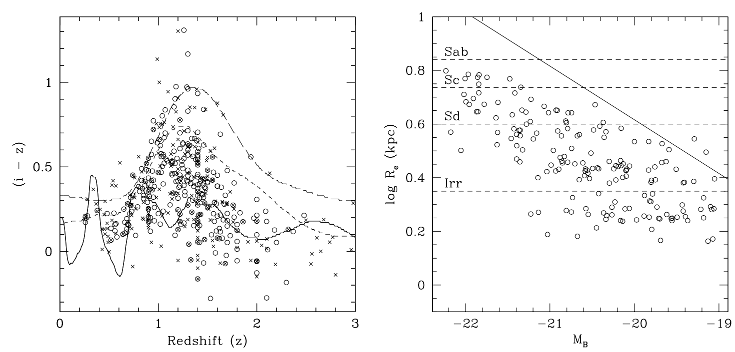

Fig. 4. Left panel: The distribution of $(i - z)$ colors for LDOs (circles) as a function of redshift with two Coleman, Wu and Weedman spectral energy distributions and a Kinney et al. starburst model plotted (see Conselice et al. 2004b). These are from bluest to reddest - starburst (solid line), Scd (dashed), Sbc (long dashed). Right panel: Absolute magnitude effective radius relationship for LDOs. The solid line is the canonical Freeman disk relationship at $z \sim 0$. The dashed horizontal lines show the effective radii of different nearby galaxy types.

account for the observed growth in stellar mass. Detailed determinations of the star formation and stellar mass build-up induced in pairs of galaxies at $z < 1$ are necessary to quantify the importance of this effect.

3.3 Disk Formation

Another major type of galaxy formation is through smooth accretion of intergalactic gas. Morphologically, systems undergoing accretion will appear as disks, with a relatively high amount of star formation than what is found in modern spirals. Some forming disks have possibly been found in deep HST imaging in the Hubble Deep Field South (Labbé et al. 2003) and the GOODS South field (Conselice et al. 2004b). These are typically found between redshifts $1 < z < 2$ and are symmetric galaxies containing bright outer regions with low central light concentrations. These bright regions create unconcentrated structures, which is how these systems are identified. Figure 2 shows examples of these luminous diffuse objects (LDOs) found in the GOODS South field (see Conselice et al. 2004b).

These systems have star formation rates consistent with starbursts (Figure 4) with typical uncorrected for extinction UV derived star formation rates of ~ 4 M_0 yr^{-1}. The integrated star formation rate in these galaxies accounts for 35-40% of the total star formation rate between redshifts $1.5 < z < 2.5$. These systems also have sizes and scaling relationships consistent with disk galaxies in formation (Figure 4). Some systems also contain structures such as spiral arms and bars (Labbé et al. 2003; Conselice et al. 2004b). The star formation rate peak found between $1 < z < 2$ appears to relate to the formation of these disk-like systems through accretion, while at lower/higher redshifts, minor/major mergers are the dominate processes.

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